A NEW SERIES OF COBALT-BASE ALLOYS FOR ADVANCED

SPACE POWER SYSTEMS

By John C. Freche, Richard L. Ashbrook, and Stanley J. Klima

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

SUMMARY

A series of cobalt-base alloys was developed for application to advanced space power systems where oxidation resistance is not required because of the vacuum environment. These alloys were designed to reduce the possibility of structural deterioration by evaporation of volatile constituents on exposure to high temperatures in space.

This alloy series compares favorably in high-temperature strength in both the cast and wrought condition with the strongest current cobalt-base alloys. Average rupture lives of 94 and 205 hours were obtained in the cast condition at 15,000 psi and 1800° F in air with two of the strongest alloys, Co-25W-1Ti-0.4C and Co-25W-1Ti-1Zr-0.4C, respectively. To date only the former alloy has been stress-rupture tested in sheet form, and a maximum rupture life of 100 hours was obtained at 10,000 psi and 1800° F in helium with solution treated sheet material.

The ductility of these alloys is sufficiently high to suggest that they could be fabricated into ducting and radiator components for turboelectric space power systems. Both alloys Co-25W-1Ti-0.4C and Co-25W-1Ti-1Zr-0.4C were readily formed into sheet by hot rolling. Maximum elongations of 25 and 23 percent, respectively, were obtained with sheet specimens of these alloys in room-temperature tensile tests.

/2541

Although oxidation resistance is not a requirement in space-power-system applications, 1900° F oxidation tests indicated that this alloy series has appreciably better oxidation resistance than unalloyed cobalt. These results as well as the long lives obtained in high-temperature stress-rupture tests in air indicated that these alloys would require only limited oxidation protection in ground-proof tests of space system components.

INTRODUCTION

Cobalt-base alloys are being used extensively for many high-strength high-temperature applications, and research is under way in various organizations to extend their capability. Among the research programs that have been conducted with cobalt-base alloys are investigations of binary and ternary systems in which refractory metals such as tungsten, molybdenum, columbium, and tantalum, as well as other metals, were added to a cobalt base (refs. 1 to 5). These investigations indicated that cobalt - refractory-metal systems have considerable potential for achieving high strength at high temperature. In particular, the investigators of reference 2 showed that the ternary compositions Co-25W-0.25C and Co-25W-5Cr had stress-rupture properties which approached those of L-605 (HS-25), a strong currently used cobalt-base alloy. Although cobalt - refractory-metal alloys would not be expected to have the high oxidation resistance of the chromium and aluminum-bearing super-alloys, there are important space-age applications such as advanced power systems for space vehicles, where oxidation resistance is not a requirement and where the cobalt - refractory-metal alloys could be advantageously employed.

Turboelectric systems, in which nuclear power is converted to electric power through the medium of a closed thermodynamic cycle, are among the most promising systems under development both for propulsion and for auxiliary power in space vehicles (ref. 6). Such systems consist of many components. These include the reactor, radiator, ducting, and various turbogenerator components. Many materials problems must be overcome to meet the design requirements of such a power system.

The ducting and radiator components pose some of the most critical materials problems. The alloys used must be ductile so that they may be readily formed. Since welded components are required for the radiator, the alloys should have adequate strength in the as-welded or welded and stress-relieved condition.

In addition to high temperatures, the external surfaces of the ducting and the radiator will be exposed to the vacuum environment of space. It has been shown (ref. 7) with several current high-temperature alloys that appreciable weight loss is incurred upon heating in a relatively low vacuum of 10^{-3} mm Hg. At 1740° F, which is in the temperature range of interest for turboelectric space power systems, a maximum weight loss of 5 percent would be expected with one of these alloys after only 18 hours of exposure. Upon long-time (10,000 hr) exposure in the much higher vacuum of space, it is conceivable that structural degradation of materials could occur as a result of the loss of highly volatile alloying constituents. Consideration of the evaporative loss rates (ref. 8) of various metals indicates that cobalt has a relatively low evaporation rate, considerably lower than nickel or iron. The refractory metals, as well as Ti, Zr, and C, have still lower loss rates.

Although the refractory metals have the lowest evaporation rates, they are generally difficult to form, require extensive protection against oxidation in ground testing, and are expensive. Therefore, as an economical means of reducing the danger of material deterioration from evaporation, cobalt-base alloys with refractory metals as the primary alloying constituents would appear to be promising. Currently available cobalt- and nickel-base alloys, on the other hand, contain high percentages of chromium and/or aluminum, both of which have high evaporation rates.

The internal surfaces of the radiator and allied ducting will be exposed to the corrosive action of the heat-transfer and turbine-drive fluids. The severity of corrosion will be directly related to the fluid used, which, in turn, depends upon the thermodynamic cycle. The fluid can be an inert gas such as argon, in which case corrosion will not be a problem. It can also be a liquid metal such as mercury or the alkali metals. Liquid metals are favored in current designs. Extensive corrosion studies made at the NASA with mercury up to 1300° F for 1000 hours have shown nickel-free cobalt-base alloys to be superior to nickel-base alloys and to nickel-bearing cobalt-base alloys (unpublished data obtained at Lewis), although inferior to the refractory metals and iron-base alloys except those containing large percentages of soluble elements such as manganese and chromium. Limited data from capsule tests with potassium at 1600° F indicate that a cobalt-base alloy had better corrosion resistance than a nickel-base alloy (ref. 9). Extensive research is still required to fully establish the relative merits of various materials with respect to alkali liquid metal corrosion.

The need for good magnetic properties and high strength at elevated

temperatures in generator rotors constitutes another major materials problem. In order not to consume energy in cooling, it is desirable for electrical generators to operate at 1500° F or above. High magnetic permeability is required to obtain efficient electric power generation. High strength is needed because of the high rotational stresses. Cobalt has the advantage of having a very high Curie temperature (1131° C), considerably higher than either iron (770° C) or nickel (358° C) (ref. 10). The cobalt - refractory-metal alloys appear to have potential for both high Curie temperature and high-temperature strength.

There are, therefore, a number of major reasons why cobalt - refractory-metal alloys should be investigated for service up to 2000° F in advanced space power systems: (1) good high temperature strength potential, (2) good fabricability potential, (3) low evaporation rates, (4) the advantage of utilizing production and fabrication capabilities developed over many years for superalloys as contrasted to the relatively new refractory-metal fabrication facilities, (5) relatively low cost as compared to refractory metals, and (6) potentially good magnetic properties at high temperatures.

Because of the potential of cobalt - refractory-metal alloys for advanced turboelectric space-power-system applications, an investigation was initiated at the NASA Lewis Research Center to provide improved alloys of this type with good high-temperature strength and sufficient ductility to make sheet. Exploratory melts of a number of cobalt - refractory-metal compositions were made. Experimental alloys were screened by stress-rupture tests at 1800° F and 15,000 psi. The most favorable composition was modified by systematic alloying additions. These modified alloys were all evaluated by stress-rupture tests and

by tensile tests at room temperature and 1800° F. Workability of the

stronger alloys was investigated by rolling. Limited oxidation tests

were also made with the stronger alloys at 1900° F.

INVESTIGATIVE PROCEDURE

Alloys Investigated

Utilizing the research background made available by other investi-

gators (refs. 1 to 5), trial melts of various binary and ternary composi-

tions that contained refractory metals as the major alloying constituents

were made. The refractory metals were chosen because of their low evapo-

ration rates in the temperature range of interest (1400° to 2000° F).

Figure 1 shows the calculated material loss in inches per 10,000 hours

in vacuum as a function of temperature for several metals as compiled

from reference 8. It should be noted that these calculations were made

for unalloyed metals and that dilution and other effects would undoubt-

edly occur in complex alloys. Samples from the trial melts were screened

for high-temperature strength and for ductility by stress-rupture tests

and swaging. A ternary alloy, Co-25W-1Ti, was selected as the basis for

systematic alloying studies. This alloy was also shown to be one of

several cobalt-tungsten alloys with promising high-temperature strength

properties in reference 2. The Co-25W-1Ti alloy was modified by system-

atic additions of two other elements, carbon and zirconium, which have

extremely low evaporation loss rates. The quantities of the additions

considered are apparent from the listing of the nominal compositions in-

vestigated (table I). All additions were made by adjusting (i.e., sub-

tracting from) the cobalt content.

Purity of Raw Materials

The purities of the alloying elements used, as determined by the suppliers, were as follows:

Element	Weight, %
Co	99.5+
Ti	99.3+
W	99.9+
Zr	99.9+
C	99.5+

Chemical Analysis

Randomly selected heats of the compositions investigated were chemically analyzed by an independent laboratory. The results of these analyses are shown in table I. Some losses in charging elements, particularly zirconium, titanium, and carbon, occurred during melting and casting. In order to minimize such losses, an inert gas (argon) cover was employed. Although this cover was used over the crucible during the entire heating and melting cycle, it could not be entirely effective in excluding air from the crucible. As might be expected, the carbon loss was greater at the greater concentrations of carbon. For example, for an addition of 0.60 C an analysis of 0.50 C was reported; for an addition of 0.10 C, 0.096 C was reported. While some loss of both titanium and zirconium was expected, it was not anticipated that the loss of zirconium would be so much greater than that of titanium. The greater negative free energy of formation value for zirconium oxide compared to that of titanium oxide may explain this greater loss of zirconium.

Casting and Inspection Techniques

The casting procedure was similar to that used in nickel-base al-loying studies made at the NASA and is described in detail in references 11 and 12. Briefly, a 50-kw, 10,000-cps water-cooled induction unit was used in melting. All melts were made in stabilized zirconia crucibles under a blanket of commercially pure argon. The charges consisted of electrolytic cobalt, ground tungsten rod, sponge titanium and zirconium, and carbon black which had previously been compressed into briquettes. Pouring tem-perature, which was measured with an optical pyrometer, was $2950^\circ \pm 50^\circ$ F. All castings were statically poured without inert gas protection into silica investment molds heated to 1600° F. The molds were allowed to cool to room temperature before the investment was removed.

The lost wax process was used to make molds of stress-rupture and tensile test bars as well as the blanks used for workability studies. The stress-rupture and tensile bars had conical shoulders and a gage section 1/4 inch in diameter and $1\frac{3}{8}$ inches long. The blanks used for workability tests were rounds nominally 1/2 inch in diameter and 3 inches long. All test bars and blanks were radiographed. They were then in-spected either with fluorescent penetrant dye or visually at a magnifi-cation of 10.

Stress-Rupture and Tensile Tests

Tables II and III show the alloys and conditions of testing for the stress-rupture tests. Cast specimens of all alloys were run in air, and some of the cast alloys were also tested in dried commercially pure he-lium at atmospheric pressure. All sheet specimens were solution treated and were tested in helium in order to prevent excessive loss of metallic

specimen cross section in long-time tests. This was considered desirable for the thin (0.050-in.) sheet specimens employed.

Tables IV and V show the alloys and conditions of testing for the tensile tests. All tensile tests were run in air. Because of the short duration of these tests, it was not considered necessary to provide an inert gas atmosphere.

Workability

The workability of the stronger alloys was investigated by making sheet from investment cast bars and by tensile tests of the sheet. The progressive steps in making sheet from investment cast blanks of alloy Co-25W-1Ti-0.4C are shown in figure 2. Cast nominally 1/2-inch rounds were heated in air to 2150° F and swaged to a diameter of 0.430 inch. Four successively smaller dies having openings of 0.538, 0.492, 0.460, and 0.430 inch were used. The swaged bars were subsequently rolled to squares approximately 0.360 inch on an edge. These rough squares were then hot rolled to sheet approximately 0.060 inch thick. The stock was heated to 2150° F between each pass and the reduction per pass was about 0.030 inch.

A similar procedure was used for making sheet from alloy Co-25W-1Ti-1Zr-0.4C. However, hot pressing was substituted for swaging as the initial step. The 1/2-inch cast rounds were pressed at 2150° F in a mechanical press to a thickness of 1/4 inch. From this point the procedure was the same. The flat bars were heated to 2150° F in air and hot rolled to 0.060 inch strips, using reductions of approximately 0.030 inch per pass.

Sheet strips of roughly 5/8 by 0.060 inch were obtained. Tensile

specimens having a test section 1 inch long by 0.175 inch by 0.050 inch
were machined from these strips.

Oxidation Tests

Test samples for oxidation tests consisted of ground cylinders
0.225 inch in diameter by 0.875 inch long. Tests were conducted in a
20-cubic-foot resistance furnace. In the furnace the samples were sus-
pended by platinum wires from alumina rods supported by an Inconel fix-
ture. The platinum wires were spot welded to one end of the cylinders.
Furnace temperature was maintained at 1900° F, and test specimens were
weighed before and after furnace exposure. The materials investigated
were tested simultaneously, and samples of each were removed after 50,
100, and 200 hours. Upon removal from the furnace, the specimens were
hung in covered glass containers to catch any spall that might come off
during cooling. After cooling, both specimens and spall, if any, were
weighed to determine weight gain.

Metallographic and X-ray Studies

Metallographic studies were made of selected alloys in both the
as-cast and worked conditions and after oxidation tests. Photomicrographs
at magnifications of 150, 250, and 750 are presented.

An X-ray determination was made of the matrix structure. Bulk
specimens rather than filings were used to avoid the possibility of
mechanically causing phase transformations in the samples. Although this
is obviously not the ideal technique for identifying minor phases, lim-
ited data were obtained by this procedure. An X-ray tube with a cobalt
target and a geiger counter recording diffractometer were used in this
work.

ALLOY EVALUATION RESULTS

Stress-Rupture Data

The results of as-cast stress-rupture tests are listed in table II. The effects of nominal carbon additions to alloy Co-25W-1Ti on stress-rupture life at 15,000 psi and 1800° F in the as-cast condition are shown in figure 3. Data were obtained in helium as well as in air. Straight lines connect the average life values obtained with each alloy. Additions of carbon of 0.3 to 0.5 percent resulted in the greatest increases in life. In air, average rupture life was increased from approximately 12 hours for the zero-carbon alloy to 160 hours for the 0.5-percent-carbon alloy (fig. 3). In helium average rupture life was increased even more, from approximately 4 hours for the zero-carbon alloy to 190 hours for the 0.4-percent-carbon alloy (fig. 3). Maximum rupture lives greater than 200 hours were obtained both in air and in helium as a result of carbon additions. The long lives obtained with these alloys in air made it apparent that a valid stress-rupture evaluation of the cast alloys in this series could be obtained without the use of an inert atmosphere. Of the several carbon-modified alloys, the Co-25W-1Ti-0.4C alloy was selected for further investigation because of its high stress-rupture properties and its excellent workability which will be discussed later.

The effects of nominal zirconium additions on the rupture life in air at 15,000 psi and 1800° F of as-cast alloy Co-25W-1Ti-0.4C are shown in figure 4. Again, straight lines were drawn between the average rupture life values obtained with each alloy. There is no well defined peak value. The average stress-rupture life was increased

from 94 to 205 hours and a maximum life of 355 hours was obtained by making zirconium additions.

Figure 5 compares the stress-rupture properties in air of two alloys, Co-25W-1Ti-0.4C and Co-25W-1Ti-1Zr-0.4C, in the as-cast condition, with several of the strongest current cast cobalt-base alloys. The commercizl alloy data were obtained from reference 13 and from Haynes Stellite data sheets. It is evident that, even though no attempts were made to protect the Co-W alloys of this investigation against oxidation by coatings, the lives of these alloys in air compare favorably with those of Stellite-31, WI-52, and Sierra alloy 302. The latter three alloys achieve oxidation resistance from large amounts of chromium, 25, 21, and 22 percent, respectively, which are present as alloying constituents.

To provide an indication of the capability of the Co-W alloys for long-time service at stress levels comparable to those expected in advanced space power system ducting applications, limited stress-rupture tests are being conducted in helium at 5000 psi. Over 7000 hours have been accumulated to date on a test bar of alloy Co-25W-1Ti-0.4C at 1800° F at this stress. Because of obvious limitations with respect to test equipment and the length of time involved, only a few such runs are being made.

Table III summarizes the stress-rupture data obtained from sheet material. A comparison of the stress-rupture properties of solution-treated sheet of alloy Co-25W-1Ti-0.4C and of two current cobalt-base sheet alloys, L-605 (HS-25) and J-1650, is presented in figure 6. The Co-W alloys were tested in helium. The commercial alloy data from reference 13 and Haynes Stellite Data Sheets were obtained in air.

Although only limited data have been obtained with the Co-W alloys to date, these data compare favorably with data for the commercial alloys. Solution treatments were the only heat treatments attempted with the Co-W alloys. It is probable that the properties could be improved by suitable aging or combinations of working and aging treatments. Further investigation is required in order to develop satisfactory procedures of this type.

Tensile and Hardness Data

Tensile test data of as-cast alloys are summarized in table IV. The effect of nominal carbon additions on the tensile properties of cast alloy Co-25W-1Ti at room temperature and 1800° F is shown in figure 7. Straight lines were drawn through the average strength and ductility values obtained with each alloy. At room temperature (fig. 7(a)) an apparent minimum in strength occurred at a 0.1-percent nominal carbon content. Ultimate strength decreased from an average value of 107,300 psi for the zero-carbon alloy to 78,000 psi for the 0.1-percent-carbon alloy. As carbon content was further increased, ultimate strength gradually increased to an average value of 105,000 psi at a 0.6-percent nominal carbon content. At 1800° F (fig. 7(b)) the zero-carbon-content alloy had less strength than any of the carbon-modified alloys. The highest average ultimate tensile strength of 44,500 psi was obtained with alloy Co-25W-1Ti-0.4C. It will be recalled that this alloy also was one of the strongest carbon-modified alloys on the basis of stress-rupture tests (fig. 3). As might be expected, the ductility of the carbon-modified alloys generally followed a trend opposite to that of tensile strength, although considerable scatter in data tends to obscure this

effect. It is interesting to note that alloy Co-25W-1Ti-0.4C retained a great deal of its strength at 1800° F. For example comparison of the average ultimate tensile strength of alloy Co-25W-1Ti-0.4C at room temperature and at 1800° F indicates that its strength at the latter temperature is approximately 46 percent of its room-temperature strength. Elongations of 6 and 12 percent at room temperature and 1800° F, respectively, were obtained with alloy Co-25W-1Ti-0.4C. Its ductility was sufficient so that it could be formed into sheet.

Table V presents data for sheet material. In the rolled condition a maximum room-temperature ultimate strength of 209,800 psi and a 25-percent elongation were obtained with this alloy. Strength and ductility in the annealed condition were also high both for alloy Co-25W-1Ti-0.4C and for the strongest (on the basis of hot tensile tests) zirconium-modified alloy Co-25W-1Ti-1Zr-0.4C. At 1800° F, maximum ultimate strengths of 37,600 and 38,400 psi as well as 15- and 22-percent elongations, respectively, were obtained with these alloys.

Hardness data are summarized in table VI. Listed values represent an average of three or more readings for each specimen. Hardness generally increased with increasing carbon content, ranging from Rockwell C-27.5 for alloy Co-25W-1Ti to C-34 for alloy Co-25W-1Ti-0.6C. The maximum Rockwell hardness of alloys Co-25W-1Ti-0.4C and Co-25W-1Ti-1Zr-0.4C was C-48 and was obtained in the as-rolled condition. After a 2400° F solution treatment, both alloys had a hardness of approximately C-28. By raising the solution treating temperatures to 2475° F, the hardness of alloy Co-25W-1Ti-0.4C was reduced to C-17.

Workability

One of the strongest carbon-modified alloys, alloy Co-25W-1Ti-0.4C,
was readily formed into sheet. The workability of the 0.2 carbon-modified
alloy was also investigated, and it too was readily formed into sheet.
As described previously, the initial step in working was to swage cast
bars. No cracks were observed in either of these alloys after the
swaging. However, the alloys containing zirconium cracked during swaging.
Cracking was more pronounced with increased zirconium content. By substi-
tuting hot pressing for swaging as the initial working step, these
alloys were also readily made into sheet. Dressing was occasionally
required to remove edge cracking which occurred during rolling with the
zirconium-modified alloys, whereas the alloys without zirconium were
almost entirely free from edge cracking and did not require dressing.

In room-temperature tensile tests, elongations up to 35, 25,
and 23 percent were obtained with sheet specimens of alloys Co-25W-1Ti-0.2C,
Co-25W-1Ti-0.4C, and Co-25W-1Ti-1Zr-0.4C, respectively (table V). These
eleongations indicate that further forming operations are possible with
these alloys. This is, of course, necessary for fabrication of radiator
components and ducting in advanced space-power-system applications.

Oxidation Data

The results of oxidation tests are shown in figure 8. Weight gain
in air at 1900° F is plotted against time of exposure. Alloys
Co-25W-1Ti-0.4C and Co-25W-1Ti-1Zr-0.4C show almost the same weight
gain, approximately 110 mg/sq cm after 200 hours. Both alloys had
better oxidation resistance than unalloyed cobalt, which showed a
weight gain of 153 mg/sq cm after 200 hours. For comparison, specimens

of WI-52, a current cast cobalt-base alloy, were simultaneously tested.
Because of the high (21 percent) chromium content of WI-52 (table I), it
would be expected that this alloy would have substantially superior oxi-
dation resistance to the Co-W alloys which contain no chromium. The test
results show this to be the case.

It should be noted from these tests that the oxidation of the
Co-W alloys of this investigation was certainly not catastrophic. This
was also evident from the stress-rupture test results, which showed rup-
ture lives as high as 355 hours at 1800° F and 15,000 psi in air for
alloy Co-25W-1Ti-1Zr-0.4C. Figure 8 also indicates that the oxidation
of these alloys followed an almost parabolic rate law. This would be
expected from the tightly adherent oxide scale present after the test.
Cracking of the oxide scale occurred only in a few samples upon cooling
from the test temperature, but spalling occurred only with the WI-52
alloy test samples. The results of these tests suggest that only lim-
ited protection against oxidation would be required in ground-proof
tests of space-system components made from these alloys. Thus, rela-
tively inexpensive facilities such as inert-gas chambers might be used
rather than ultra-high vacuum facilities.

Metallographic Studies

Figure 9 presents photomicrographs of alloy Co-25W-1Ti and various
carbon modifications of this alloy at X250 and X750. The effects of
carbon additions on microstructure are evident. A major feature to be
noted is the increase in the number and size of the carbide particles
with increasing carbon content. These appear as a noncontinuous inter-

dendritic carbide network which is particularly obvious in the 0.4C

modified alloy (fig. 9(c)). Even when no carbon was intentionally added

as in alloy Co-25W-1Ti (0.022 percent carbon by chemical analysis), there

were a limited number of idiomorphic microconstituents, probably TiC

or TiCN, present.

A Widmanstätten structure was observed, particularly in the range

of intermediate carbon additions (figs. 9(b) and (c)). A microconstituent

with a similar appearance was identified (ref. 1) as W_2Co_7 precipitate in

a matrix of β face-centered cubic solid solution in the alloy Co-35W,

heated for 50 hours at 1832° F. The phase W_2Co_7 has been identified as

WCo_3 by later investigators (ref. 14). In current notation the face-

centered cubic solid solution is designated as α rather than as β

(ref. 14). The investigators of reference 2 referred to a similar

structure found in a Co-25W binary alloy aged for 256 hours at 1652° F

as "Widmanstätten ϵ".

Figure 10 shows photomicrographs (X250 and X750) of the as-cast

alloy Co-25W-1Ti-1Zr-0.4C. There is not evidence of a Widmanstätten

structure. The appearance of the interdendritic carbide network has

been modified by the addition of zirconium.

Photomicrographs at X250 and X750 of alloy Co-25W-1Ti-0.4C after

working are shown in figure 11. The changes in microstructure brought

about by rolling at 2150° F are apparent from figure 11(a). The

microconstituents have been stringered by the working process and there

is evidence of twinning.

Figure 11(b) shows the rolled alloy after a 16-hour solution heat

treatment at 2400° F. This heat treatment dissolved virtually all of

the minor phases, although some of the carbonitrides were not dissolved. Some etch pits, which are similar in appearance to carbides, are present in the specimen. Numerous attempts were made to avoid their formation during etching, without success.

The microstructures of both alloy Co-25W-1Ti-0.4C and Co-25W-1Ti-1Zr-0.4C after a 50-hour oxidation test at 1900° F are shown in figure 12 at X150. The oxide scale is divided into three layers in both alloys. This oxide scale is believed to be CoO, the stable oxide at the test temperature of 1900° F (ref. 14). The interface between the outer and middle oxide layers may mark the original specimen surface. What appear to be grain boundaries are discernible in the outer oxide layer, particularly in alloy Co-25W-1Ti-0.4C. In both alloys a thin internally oxidized zone is apparent within the metal matrix along the metal-oxide interface.

X-ray Determination

Samples from cast alloy Co-25W-1Ti-0.4C before and after stress-rupture testing, as well as from solution treated Co-25W-1Ti-0.2C alloy sheet, were examined. In all the samples the matrix was shown to be a face-centered cubic solid solution of α Co. The possible presence of the intermetallic compound Co_3W was noted in the as-cast 0.4 carbon-modified alloys, while none was detected in the solution-treated sheet. Only limited evidence of the presence of the ϵ Co phase was obtained for all the samples. There was no clear evidence of the MC type of carbides, although their presence would be expected.

CONCLUDING REMARKS

Although much additional information must be obtained in order to describe fully the properties of this alloy series, the data presented indicate that it has considerable potential for turboelectric space-

power-system applications. Because the alloys contain only low-vapor-
pressure alloying constituents, they are inherently more resistant to
evaporation in a space environment than superalloys that contain chromium
and aluminum. The excellent high-temperature strength of these Co-W al-
loys compares favorably with current cobalt-base alloys. The Co-W alloys
also have been shown to have excellent workability. Subject to their
ability to withstand corrosion by the heat-transfer fluids, these alloys
appear attractive for ducting and turbine components of turboelectric
space power systems. The combination of potential high Curie temperature
and high-temperature strength makes this alloy system also appear attrac-
tive for electrical generating components of these systems.

In order to exploit the potential of these alloys, it is suggested
that additional research be conducted. In particular, additional long-
and short-time strength data in high vacuum as well as in helium must be
obtained for sheet material, and weldability as well as possible effects
of welding upon sheet properties investigated. The possibility of em-
brittlement caused by long-time use at high temperatures should be in-
vestigated. Also, the potential benefits of heat treatment or combined
working and heat treatment on strength should be explored. Resistance
to alkali metal corrosion above 1300° F must be investigated more fully,
and protective coatings should be considered as a means of extending the
use of these alloys to service in air. Finally, the magnetic properties
at high temperatures should be determined, in order to evaluate these
alloys for applicability to the electrical generating equipment. In all
of these areas, additional alloying approaches should be considered to
optimize material properties.

SUMMARY OF RESULTS

The following major results were obtained from an investigation to provide cobalt-base alloys for application to advanced turboelectric space power systems:

1. A series of cobalt-base alloys was developed which utilized only elements with extremely low evaporative loss rates as alloying constituents in order to minimize possible structural deterioration by evaporation of volatile constituents in space applications.

2. This alloy series compares favorably in high-temperature strength in both the as-cast and wrought condition with the strongest current cobalt-base alloys. Average rupture lives of 94 and 205 hours were obtained in the cast condition at 15,000 psi and 1800° F in air with two of the strongest alloys, Co-25W-1Ti-0.4C and Co-25W-1Ti-1Zr-0.4C, respectively. A maximum rupture life of 100 hours was obtained at 10,000 psi and 1800° F in helium with solution-treated sheet made from the former alloy.

3. The strongest high-temperature alloys in this series, Co-25W-1Ti-0.4C and Co-25W-1Ti-1Zr-0.4C, were readily formed into sheet by hot rolling. Maximum elongations of 25 and 23 percent, respectively, were obtained in room-temperature tensile tests with sheet specimens of these alloys. This suggests that these alloys could be fabricated into ducting and radiator components for advanced turboelectric space power systems.

4. Although oxidation resistance is not a requirement in space-power-system application, oxidation tests at 1900° F indicate that these alloys have considerably better oxidation resistance than unalloyed cobalt. These results, as well as long-time stress-rupture tests in

air, suggest that only limited oxidation protection would be required in ground-proof tests of space-system components made from these alloys.

REFERENCES

1. Sykes, W. P.: The Cobalt-Tungsten System. Trans. Am. Soc. Steel Treating, vol. 21, 1933, pp. 385-423.

2. Adkins, E. F., Williams, D. N., and Jaffee, R. I.: Development of Wrought Cobalt-Tungsten-Base Alloys. Cobalt, No. 8, Sept. 1960.

3. Lux, B., and Bollmann, W.: Precipitation Hardening of Co-Base Alloys by Means of an Intermetallic Co-Mo Phase. Cobalt, No. 11, June 1961, pp. 4-20

4. Fritzlen, G. A., Faulkner, W. H., Barrett, B. R., and Fountain, R. W.: Precipitation in Cobalt-Base Alloys. Precipitation from Solid Solution. ASM (Cleveland), 1959.

5. Rausch, J. J., Simcoe, C. R., and Levinson, D. W.: "Development of Cobalt-Base Alloys." Final Rep. ARF 2131-9 for Dept. Navy, Armour Res. Foundation, Feb. 4, 1960. (Contract NOas 58-136C.)

6. Slone, Henry O., and Lieblein, Seymour: Electric Power Generation Systems for Use in Space. 2nd Int. Cong. ICAS, Zurich (Switzerland), Sept. 1960.

7. Bates, R. C.: Evaporation Rates of Several Alloys in Vacuum at High Temperature. Metal Treating, Oct.-Nov. 1961.

8. Dushmann, Saul: Scientific Foundations of Vacuum Techniques. Second ed., J. M. Lafferty, ed., John Wiley & Sons, Inc., 1962.

9. Hoffmann, Eugene E.: Boiling Alkali Metal and Related Studies. Oak Ridge National Lab. NASA TN D-769, 1961.

10. Ascher, E., and Janner, A.: Why Cobalt for Magnetic Development? Cobalt, No. 7, June 1960. p. 3

11. Freche, John C., and Waters, William J.: Exploratory Investigation of Advanced-Temperature Nickel-Base Alloys. NASA MEMO 4-13-59E, 1959.

12. Freche, John C., Riley, Thomas J., and Waters, William J.: Continued Study of Advanced-Temperature Nickel-Base Alloys to Investigate Vanadium Additives. NASA TN D-260, 1960.

13. Wagner, H. J., and Hall, A. M.: The Physical Metallurgy of Cobalt-Base Superalloys. DMIC Rep. 171, July 6, 1962.

14. Hansen, Max, and Andrenko, Kurt: Constitution of Binary Alloys. Second ed., McGraw-Hill Book Co., Inc., 1958.

TABLE I. - ALLOY COMPOSITIONS

(a) Alloys investigated

Alloy	Actual composition of typical heats, weight %				
	Co	W	Ti	Zr	C
Co-25W-1Ti	74.31	24.95	0.54	ND[a]	0.022
Co-25W-1Ti-0.1C	72.66	26.41	.85	ND	.096
Co-25W-1Ti-0.2C	72.62	26.05	.90	0.01	.17
Co-25W-1Ti-0.3C	72.43	26.42	.92	ND	.286
Co-25W-1Ti-0.4C	72.83	25.84	.98	ND	.334
Co-25W-1Ti-0.5C	Bal.	24.19	.99	----	.44
Co-25W-1Ti-0.6C		24.24	1.06	----	.50
Co-25W-1Ti-0.25Zr-0.4C		24.97	.91	.13	.34
Co-25W-1Ti-1Zr-0.4C		24.18	1.17	.51	.42
Co-25W-1Ti-1.5Zr-0.4C		24.97	.96	1.13	.45
Co-25W-1Ti-2Zr-0.4C		25.00	.97	1.41	.43

(b) Commercial alloys (data from ref. 13)

Alloy	Nominal composition, weight %										
	Co	Cr	Ni	W	Cb	Ta	Fe	Ti	B	Zr	C
WI-52	Bal.	21		11	2		2				0.45
L-605 (HS 25)		20	10	15			1				.10
HS 31		25	10	8			1.5				.50
J-1650		19	26	12	2			4	0.02		.2
SM 302		22		10		9			.005	0.20	.85

[a]Not detectable or less than 0.01

TABLE II. - SUMMARY OF AS-CAST STRESS-RUPTURE DATA

Alloy	Test temperature, °F	Stress, psi	Atmosphere	Life, hr
Co-25W-1Ti	1800	15,000	Air	9.3
			Air	15.8
			Helium	2.8
			Helium	5.4
Co-25W-1Ti-0.1C	1800	15,000	Helium	9.7
Co-25W-1Ti-0.1C	1800	15,000	Helium	16.8
Co-25W-1Ti-0.2C	1800	15,000	Air	13.6
				22.3
				16.6
			Helium	114.1
				58.5
				123
				22.5
				33.2
Co-25W-1Ti-0.3C	1800	15,000	Air	25.5
				116.7
				174.9
				39.2
			Helium	115.6
				86.8
				25.2
				207.3
Co-25W-1Ti-0.4C	1700	15,000	Air	734.8
		15,000		544.3
		17,500		104.8
		17,500		108.5
		22,500		38.4
		22,500		57.1
	1800	10,000		595.2
		10,000		746.6
		15,000		109.0
				78.9
				98.6
				89.2
		17,500		26.7
		17,500		30.3
		20,000		7.7
		20,000		26.5
		15,000	Helium	179.4
				150.3
				239.2
				194.7
		5,000		7000+

TABLE II. - Concluded. SUMMARY OF AS-CAST STRESS-RUPTURE DATA

Alloy	Test temperature, °F	Stress, psi	Atmos-phere	Life, hr
Co-25W-1Ti-0.5C	1800	15,000	Air	94.7
			Air	226.8
			Helium	130.8
				132.3
				214
				116.8
Co-25W-1Ti-0.6C	1800	15,000	Air	62.1
				34.7
				48.7
			Helium	63
				55.1
				116.5
				107.7
Co-25W-1Ti-0.25Zr-0.4C	1800	15,000	Air	162.9
Co-25W-1Ti-0.25Zr-0.4C	1800	15,000	Air	184.0
Co-25W-1Ti-1Zr-0.40	1800	12,500	Air	161.2
				478.8
				245.6
		15,000		355.1
				118.5
				209.6
				210.7
				129.6
		20,000		12.2
		20,000		26.1
Co-25W-1Ti-1.5Zr-0.4C	1800	15,000	Air	180.0
Co-25W-1Ti-1.5Zr-0.4C	1800	15,000	Air	154.0
Co-25W-1Ti-2Zr-0.4C	1800	15,000	Air	158.8
Co-25W-1Ti-2Zr-0.4C	1800	15,000	Air	127.5

TABLE III. - SUMMARY OF SHEET STRESS-RUPTURE DATA

Alloy	Condition (a)	Test temperature, °F	Stress, psi	Atmosphere	Life, hr
Co-25W-1Ti-0.4C	ST:2400° F, 16 hr	1800	7,500 10,000 10,000 15,000 15,000	Helium	53.4 30.9 47.8 7.7 6.7
	ST:2475° F, 16 hr	1800	10,000 15,000 15,000	Helium	100.4 10.3 15.0

aSolution treatments performed in argon, followed by water quench.

TABLE IV. - SUMMARY OF AS-CAST TENSILE DATA

Alloy	Test temperature, °F	Yield strength, psi	Ultimate tensile strength, psi	Elongation, %	Reduction in area, %
Co-25W-1Ti	Room	85,000	114,600	23	19
Co-25W-1Ti	Room	83,000	100,000	22	26.8
Co-25W-1Ti	1800	------	36,600	17	18.6
Co-25W-1Ti-0.1C	Room	61,800	78,100	8	14.8
Co-25W-1Ti-0.2C	Room	71,400	86,500	6	9.8
Co-25W-1Ti-0.2C		71,300	89,000	7	9.3
Co-25W-1Ti-0.3C		76,000	96,500	4.7	8.5
Co-25W-1Ti-0.3C		80,500	99,500	4.7	6.2
Co-25W-1Ti-0.4C		79,100	104,500	7.0	8.5
Co-25W-1Ti-0.4C		68,200	86,700	6.9	12.8
Co-25W-1Ti-0.4C		79,000	99,800	4.7	5.7
Co-25W-1Ti-0.6C		83,500	96,200	2.3	8.4
Co-25W-1Ti-0.6C		88,200	114,000	4.7	11.0
Co-25W-1Ti-0.2C	1800	------	39,600	16.4	17.8
Co-25W-1Ti-0.2C		------	37,100	----	30.7
Co-25W-1Ti-0.3C		------	45,000	10.9	14.9
Co-25W-1Ti-0.3C		------	39,200	10.9	12.9
Co-25W-1Ti-0.4C		------	45,100	11	9.1
Co-25W-1Ti-0.4C		------	44,500	----	18.6
Co-25W-1Ti-0.4C		------	45,000	14	19.4
Co-25W-1Ti-0.6C		------	39,800	14.1	21.5
Co-25W-1Ti-0.6C		------	36,700	10.9	7.8

TABLE V. - SUMMARY OF SHEET TENSILE DATA

Alloy	Condition (a)	Test temper- °F	Yield strength, psi	Ultimate tensile strength, psi	Elonga- tion, %	Reduction in area, %
Co-25W-1Ti-0.2C	ST:2400° F, 16 hr	Room	81,500	154,500	30	21.2
Co-25W-1Ti-0.2C	ST:2400° F, 16 hr	Room	85,200	161,000	35	26.2
Co-25W-1Ti-0.4C	As-rolled	Room	130,400	199,000	20.3	22.0
	As-rolled		143,500	209,800	25.0	24.4
	ST:2475° F, 16 hr		65,000	115,500	13.3	15.6
	ST:2475° F, 16 hr		60,200	96,500	15.6	18.2
	ST:2400° F, 16 hr		75,800	139,000	20.3	15.8
			77,900	149,500	20.3	16.8
		1800	-------	37,600	15	----
		1800	-------	32,000	16	----
Co-25W-1Ti-1Zr-0.4C	ST:2400° F, 16 hr	Room	76,900	150,300	23	17.8
Co-25W-1Ti-1Zr-0.4C		Room	79,600	143,750	18	12.5
Co-25W-1Ti-1Zr-0.4C		1800	-------	38,100	17	----
Co-25W-1Ti-1Zr-0.4C		1800	-------	38,400	22	----

[a]Solution treatments performed in argon, followed by water quench.

TABLE VI. - SUMMARY OF HARDNESS DATA

Alloy	Average Rockwell C hardness	Condition
Co-25W-1Ti	27.5	As-cast
Co-25W-1Ti-0.1C	30	
Co-25W-1Ti-0.2C	28.5	
Co-25W-1Ti-0.3C	30.4	
Co-25W-1Ti-0.4C	29.5	
Co-25W-1Ti-0.5C	33	
Co-25W-1Ti-0.6C	34	
Co-25W-1Ti-0.4C	48	As-rolled
	28	Solution treated at 2400° F
	17	Solution treated at 2475° F
Co-25W-1Ti-1Zr-0.4C	32	As-cast
	48	As-rolled
	28.5	Solution treated at 2400° F
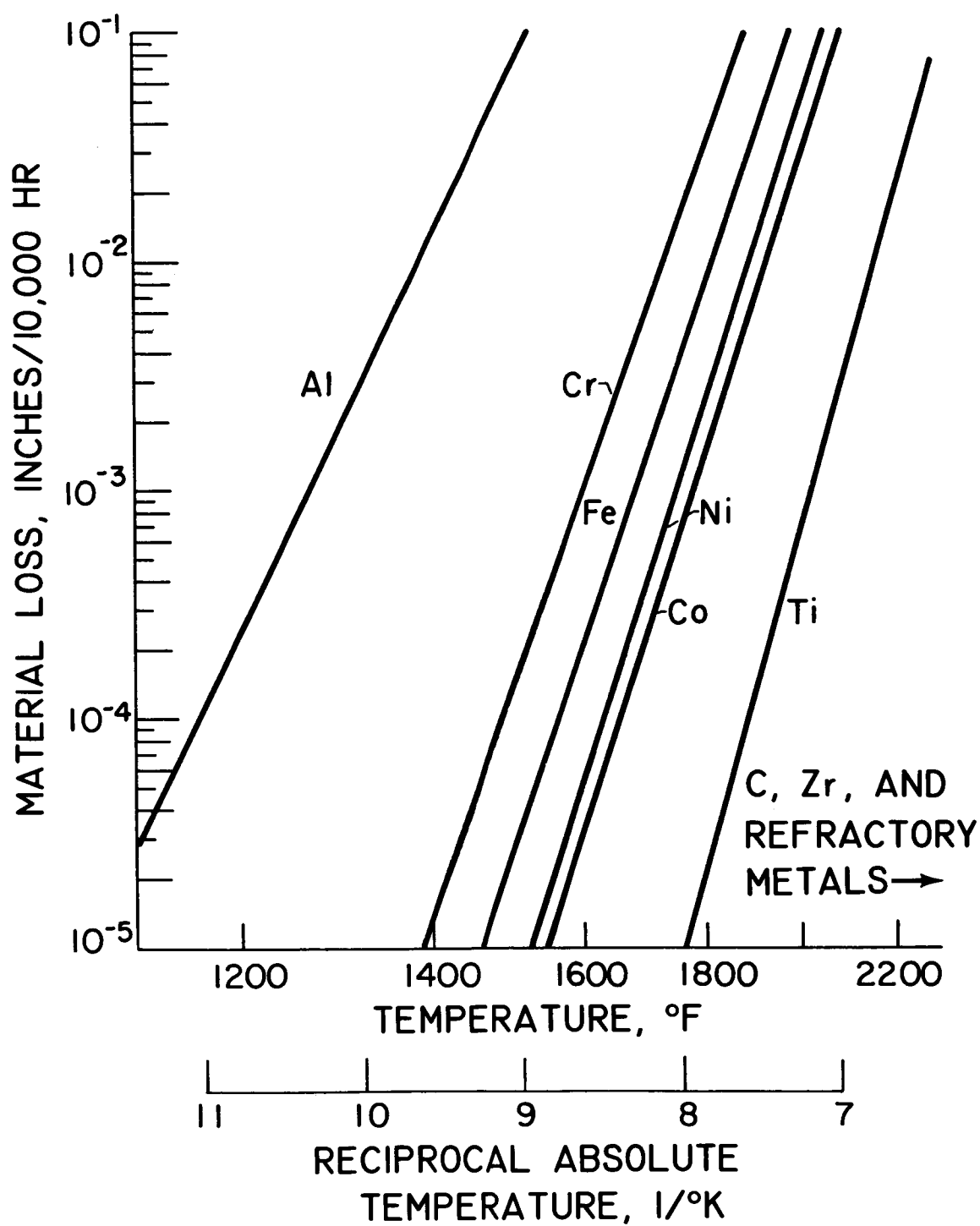
Figure 1. - Material loss in vacuum as a function of temperature for several metals.
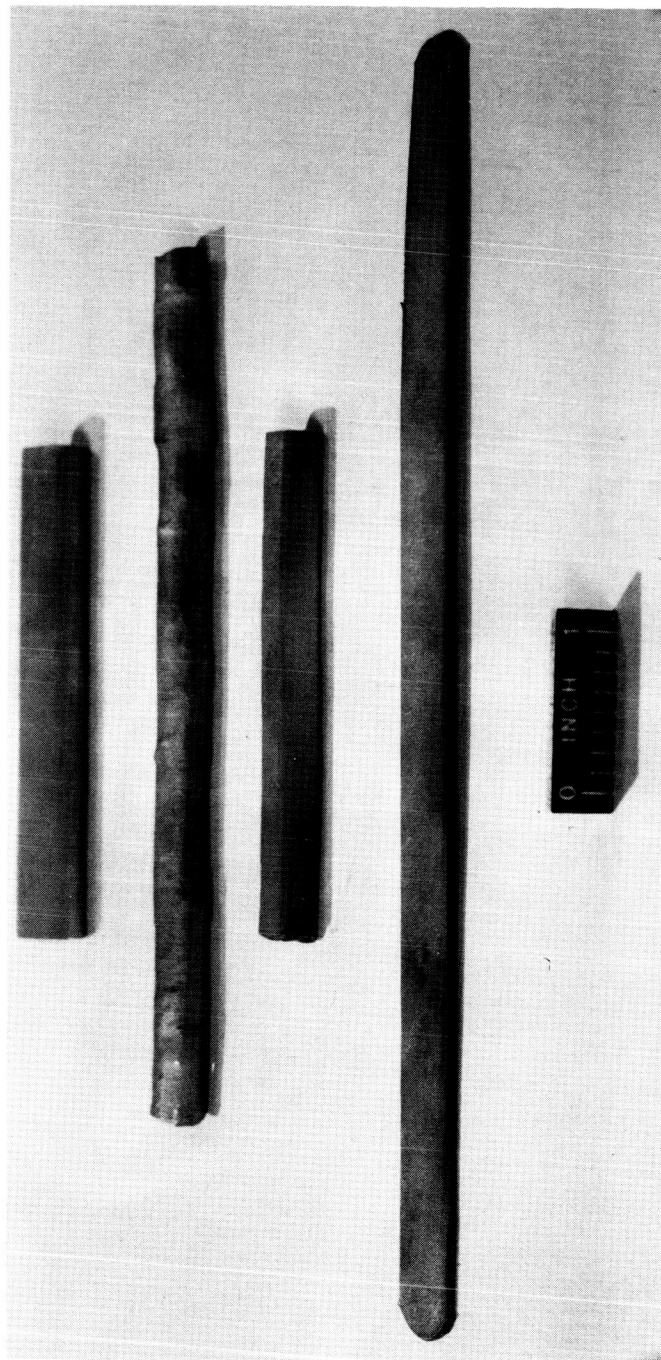
C-58450
CS-23554

Figure 2. - Progressive steps in making sheet from cast rounds of alloy Co-25W-1Ti-0.4C. Top to bottom: (1) cast 1/2-in. round, (2) swaged 0.430-in. round, (3) rolled 0.360-in. square, (4) rolled strip 5/8 × 0.060-in.
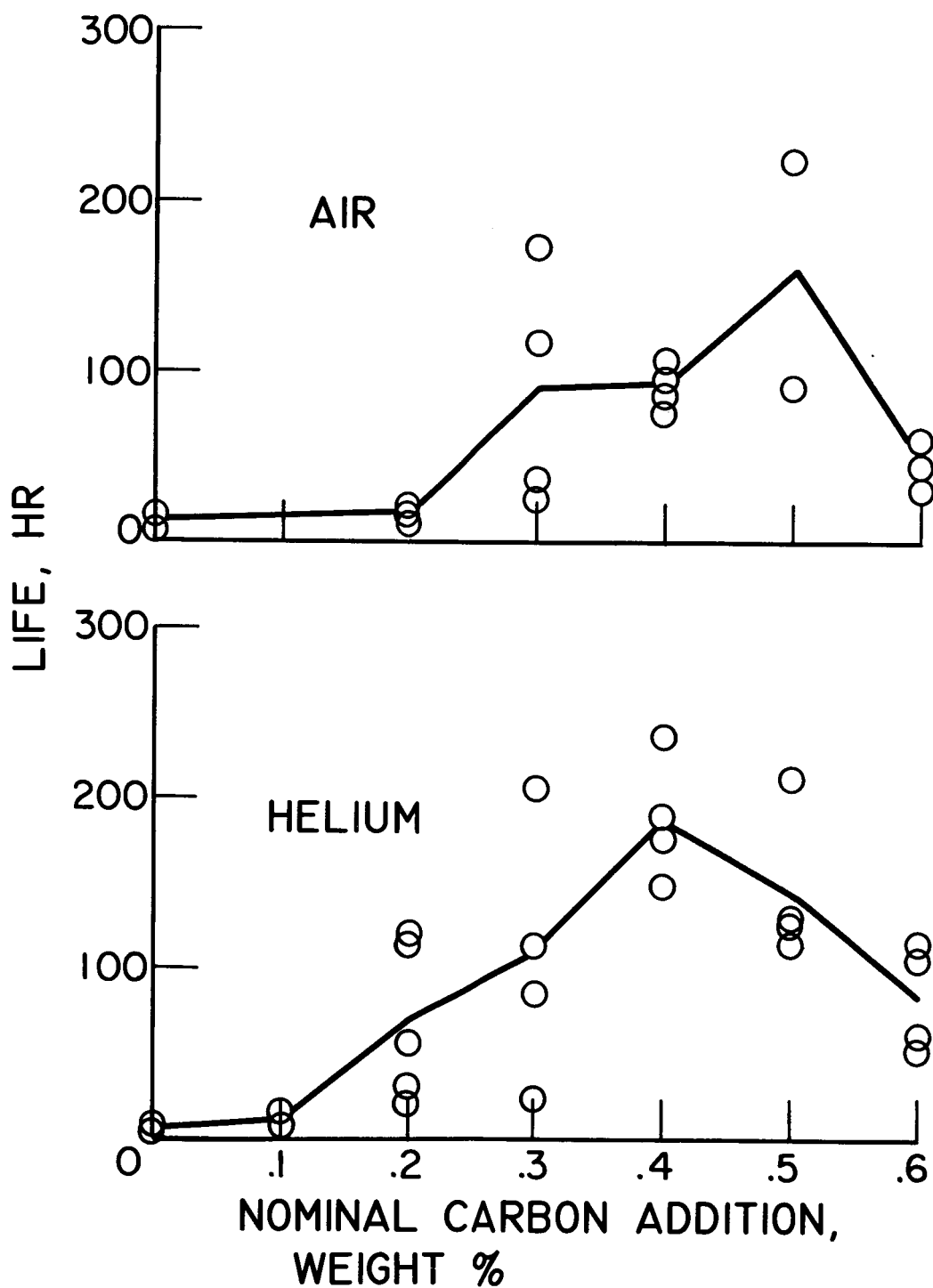
Figure 3. - Effect of carbon additions on rupture life of alloy Co-25W-1Ti at 15,000 psi and 1800° F in as-cast condition, tested in air and in helium. (See table I for chemical analysis of alloys.)

Figure 4. - Effect of zirconium additions on rupture life of alloy Co-25W-1Ti-0.4C at 15,000 psi and 1800° F in as-cast condition. (See table I for chemical analysis of alloys.)
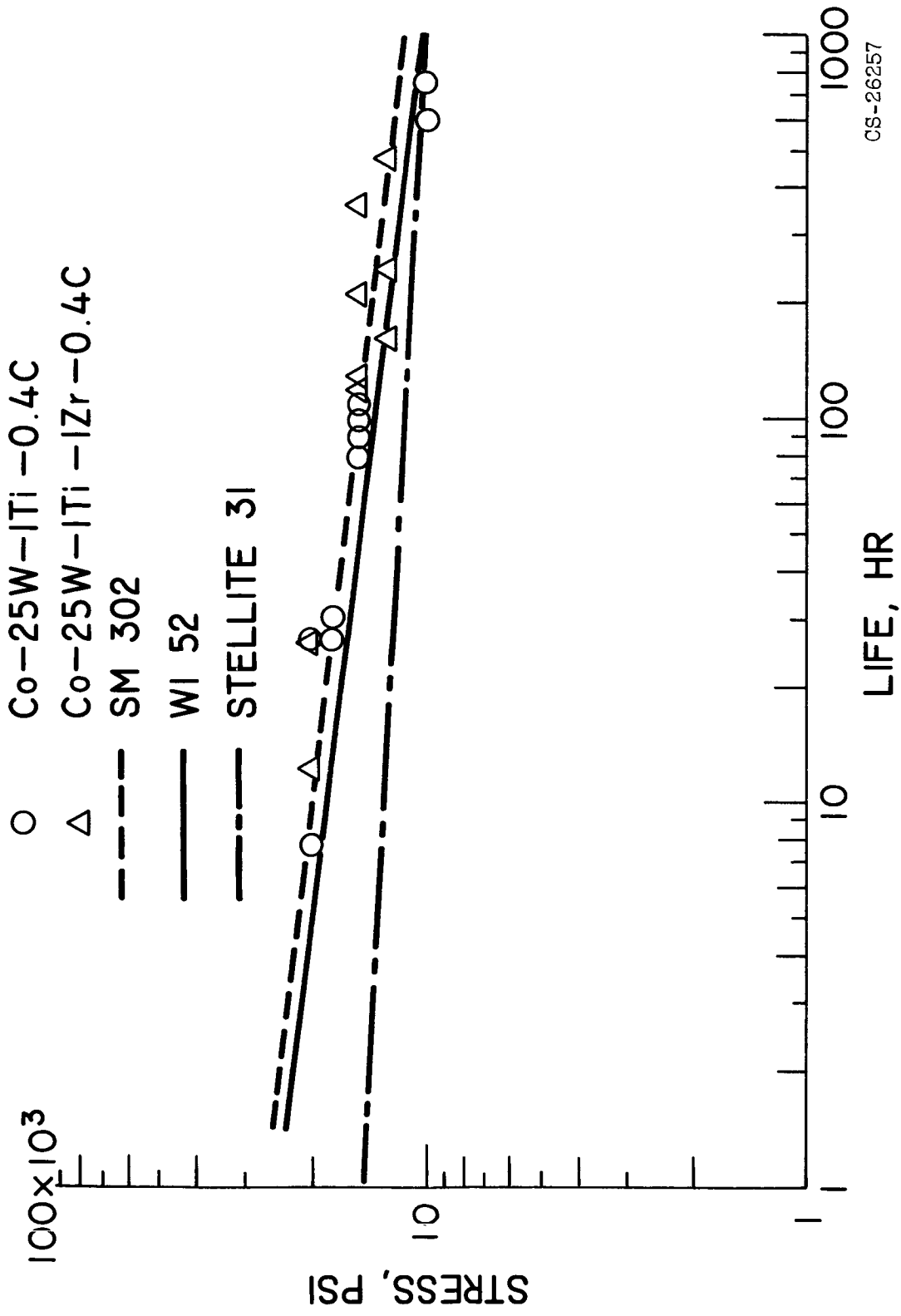
Figure 5. - Comparison of stress-rupture properties of several cast cobalt base alloys at 1800° F in air.

CS-26257
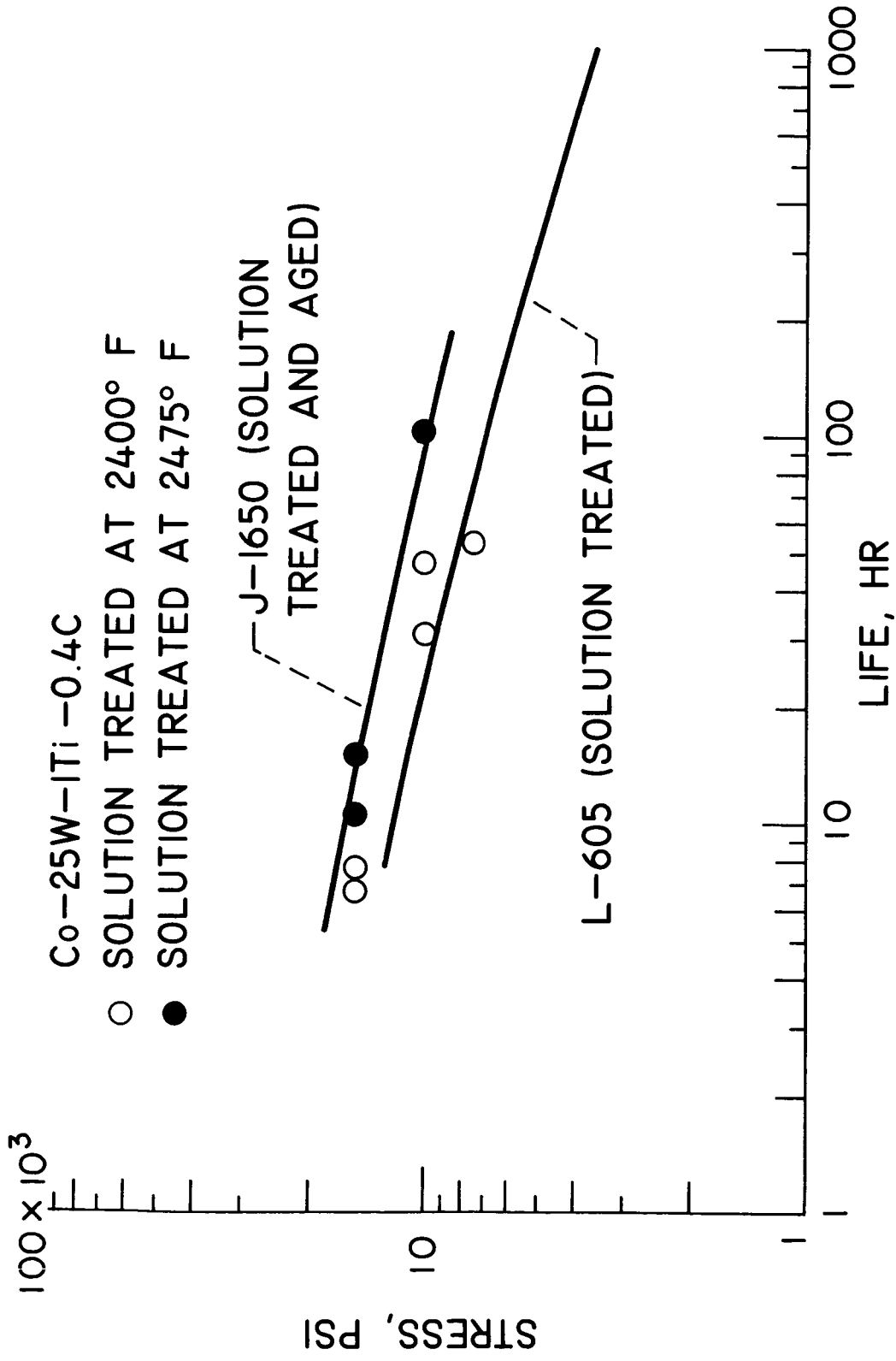
Figure 6. - Stress-rupture properties of Co-25W-1Ti-0.4C alloy sheet at 1800° F in helium compared to current cobalt base sheet alloys.
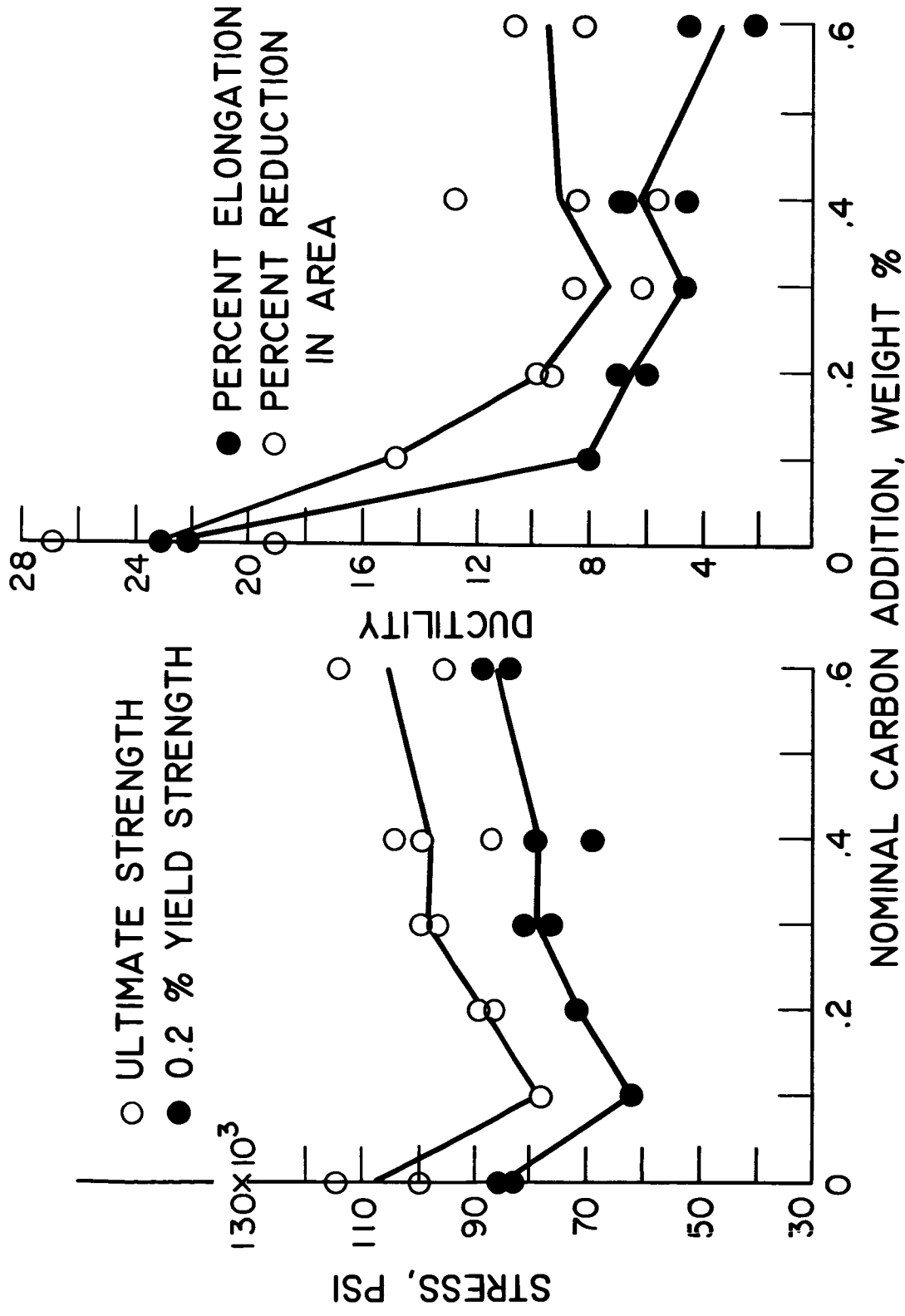
(a) Room temperature.

Figure 7. - Effect of carbon additions on tensile properties of cast alloy Co-25W-1Ti.
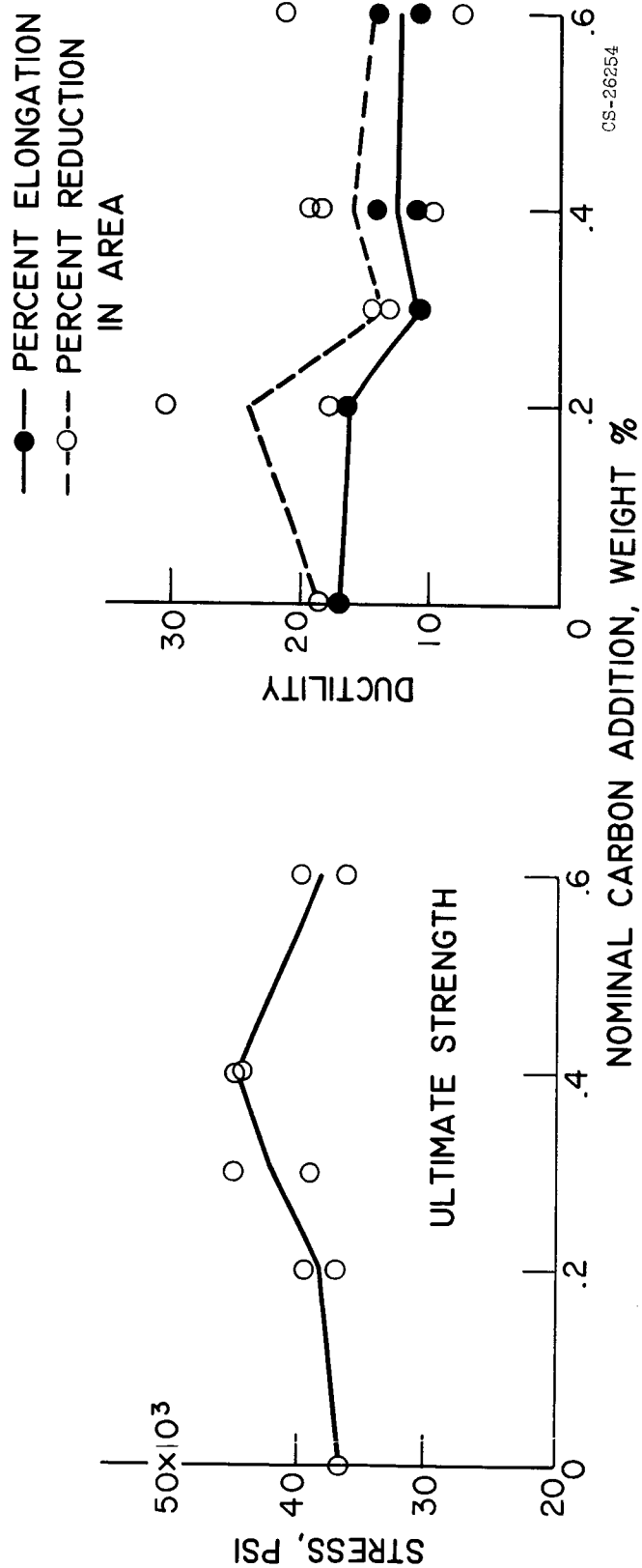
(b) 1800° F.

Figure 7. - Concluded. Effect of carbon additions on tensile properties of cast alloy Co-25W-1Ti.
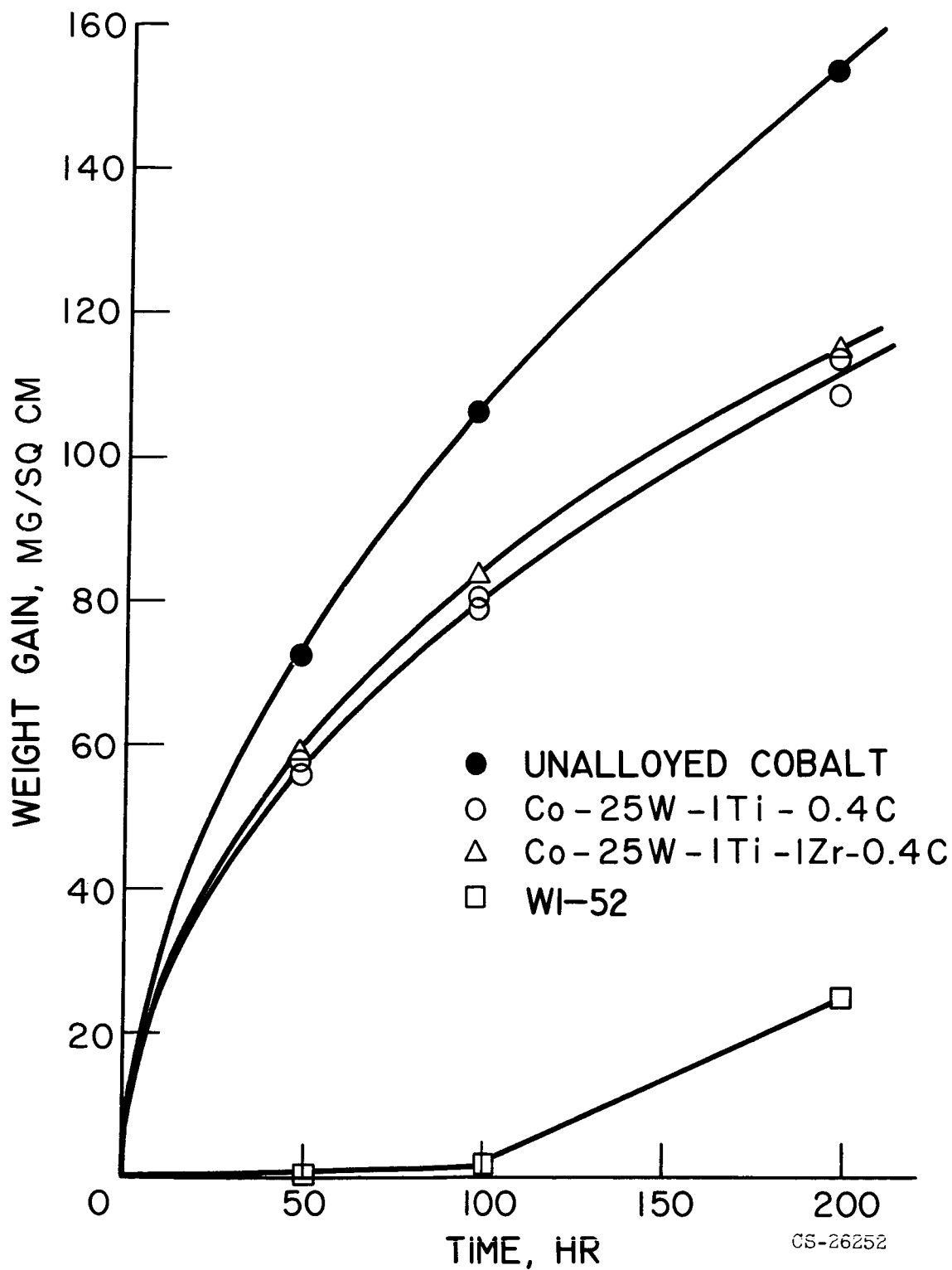
Figure 8. - Weight gain per unit area as a function of time in air at 1900° F.

×250

×250

C-64233

├────────┤
I INCH
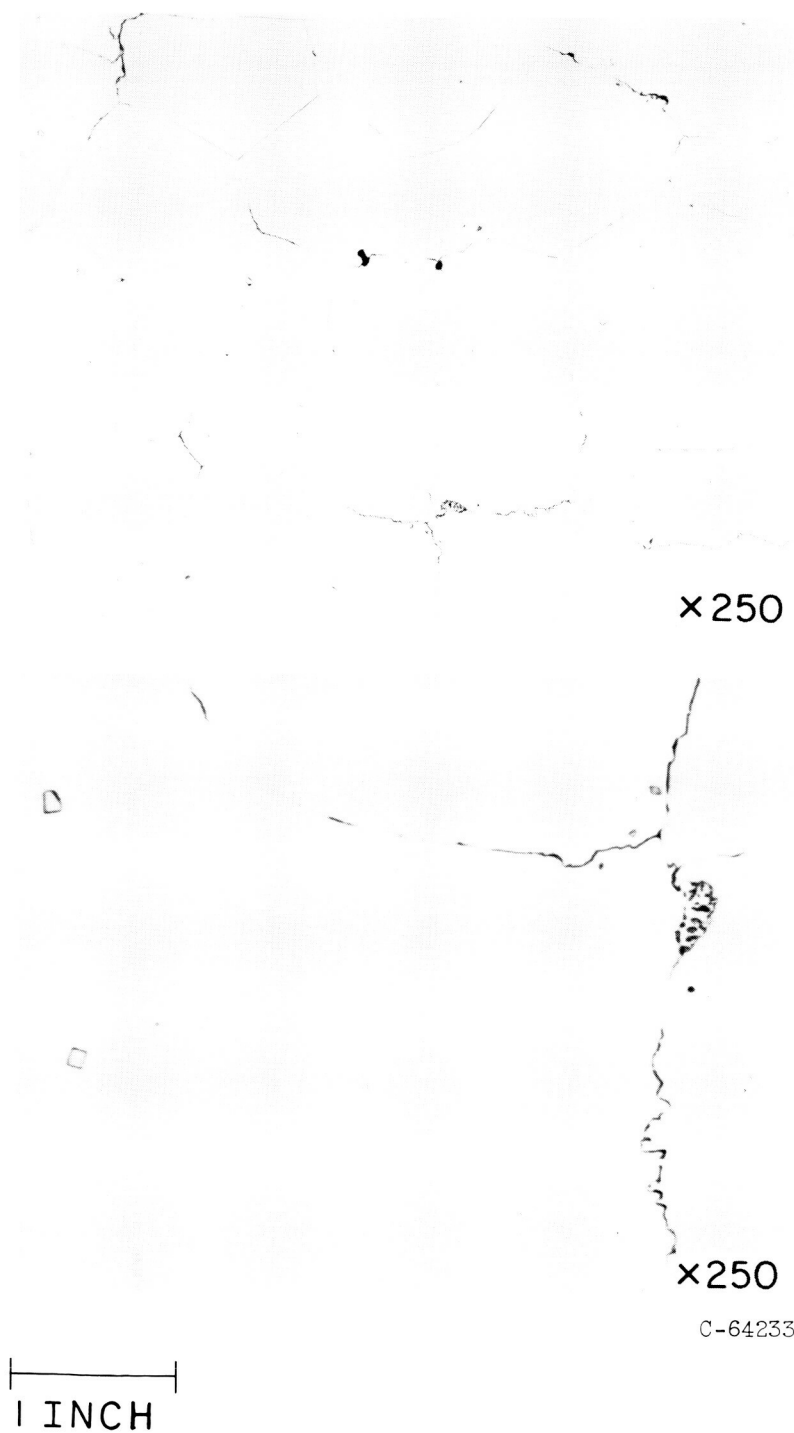
(a) Alloy Co-25W-1Ti.

Figure 9. - Effect of carbon additions on the as-cast microstructure of the alloy Co-25W-1Ti.

× 250

× 750
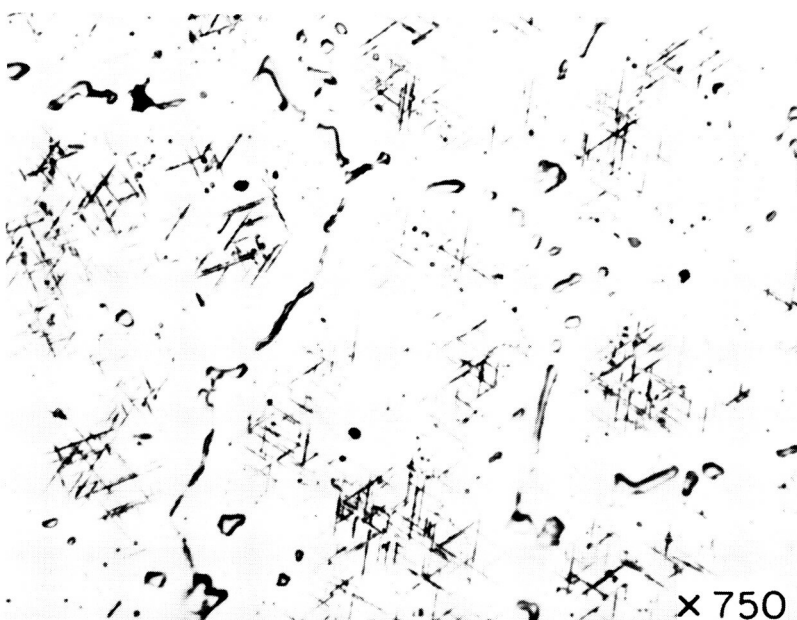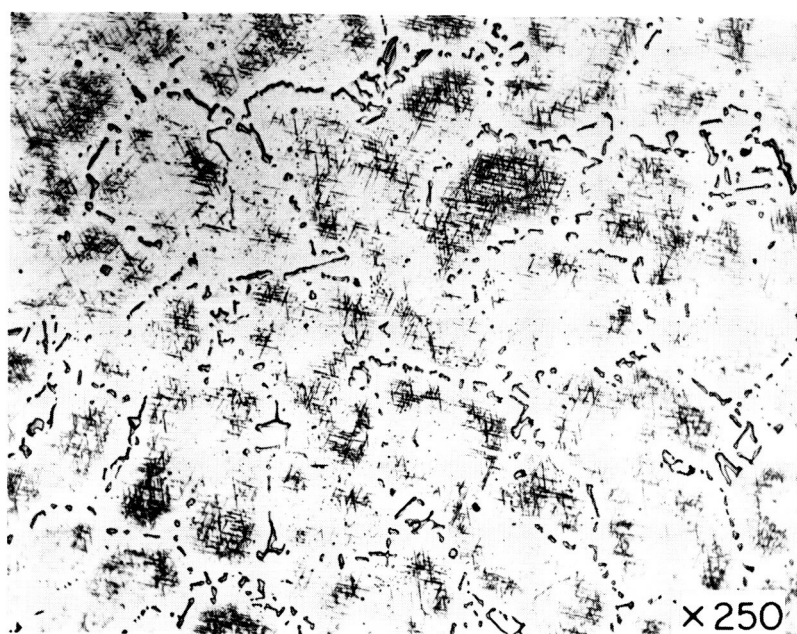
C-64230

|⊢——————⊣|
I INCH

(b) Alloy Co-25W-1Ti-0.2C.

Figure 9. - Continued. Effect of carbon additions on the
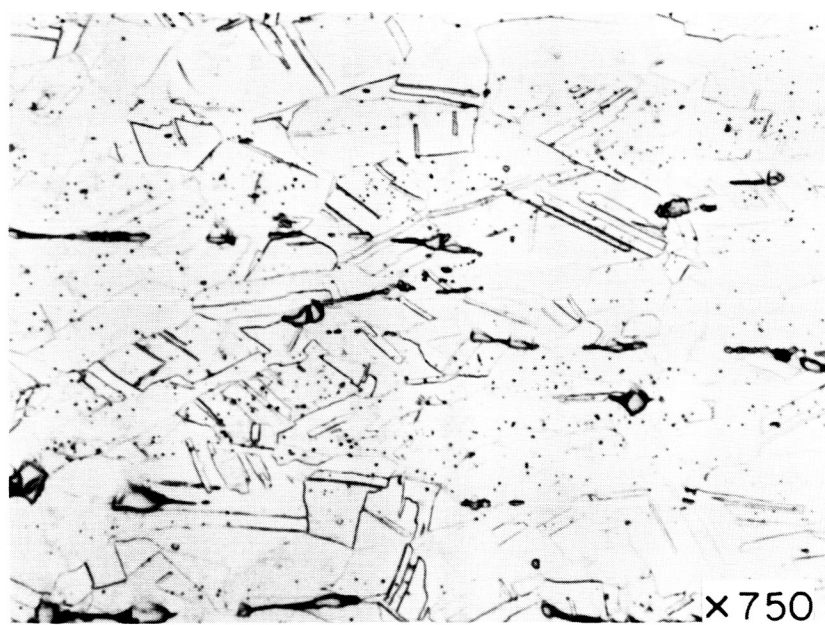as-cast microstructure of the alloy Co-25W-1Ti.

× 250

× 750

C-64232

├─────────────┤
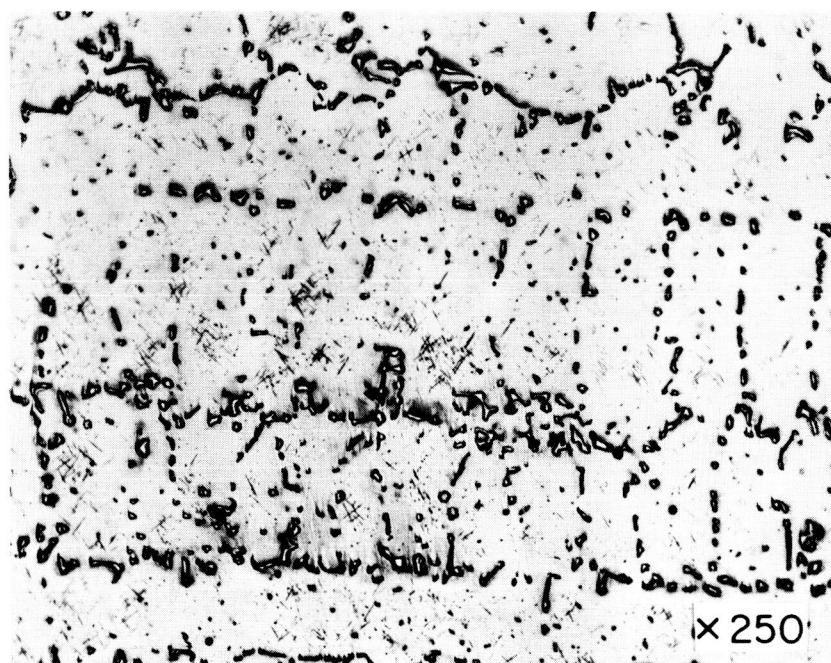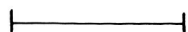
I INCH

(c) Alloy Co-25W-1Ti-0.4C.

Figure 9. - Continued. Effect of carbon additions on the
as-cast microstructure of the alloy Co-25W-1Ti.

×250

×750

C-64231

├─────────────┤
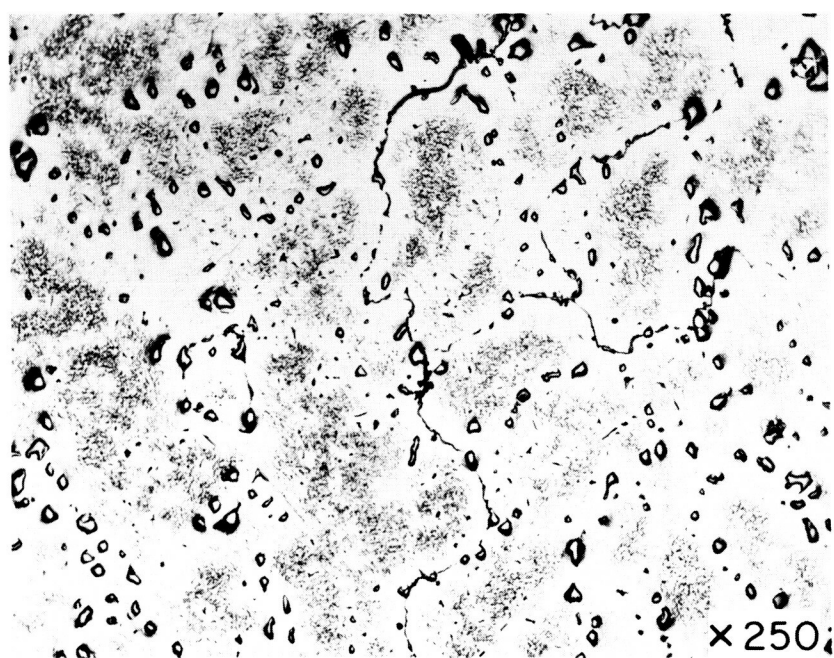
I INCH

(d) Alloy Co-25W-1Ti-0.6C.

Figure 9. - Concluded. Effect of carbon additions on the
as-cast microstructure of the alloy Co-25W-1Ti.

× 250

× 750

C-64229

├───────────┤
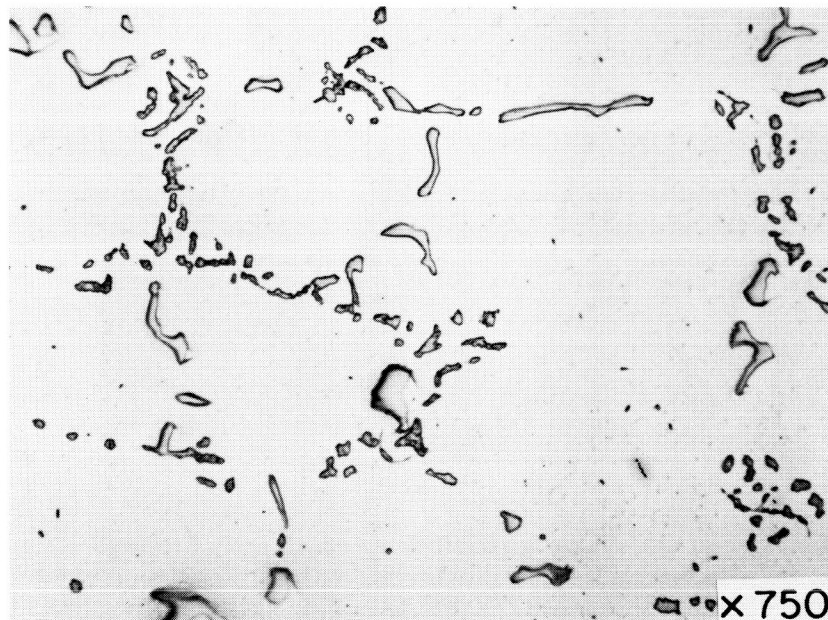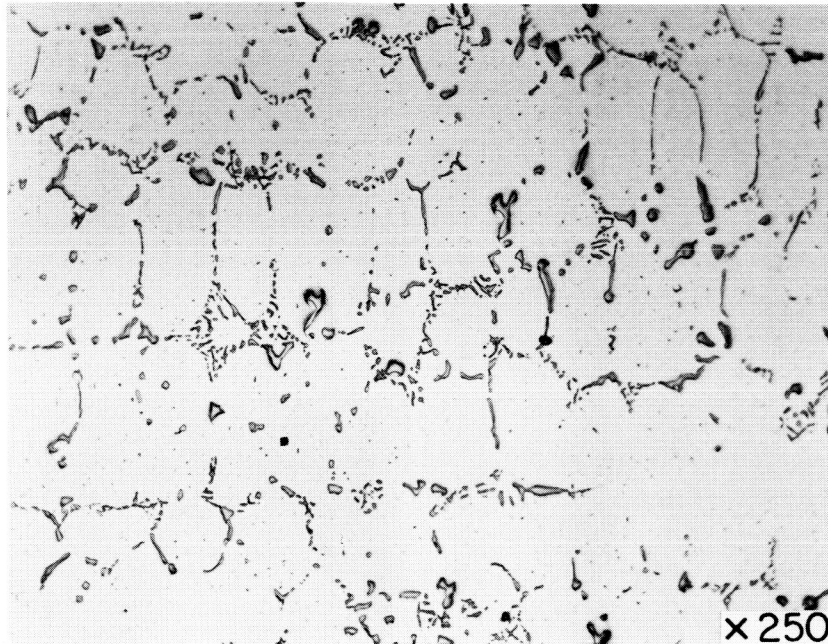
I INCH

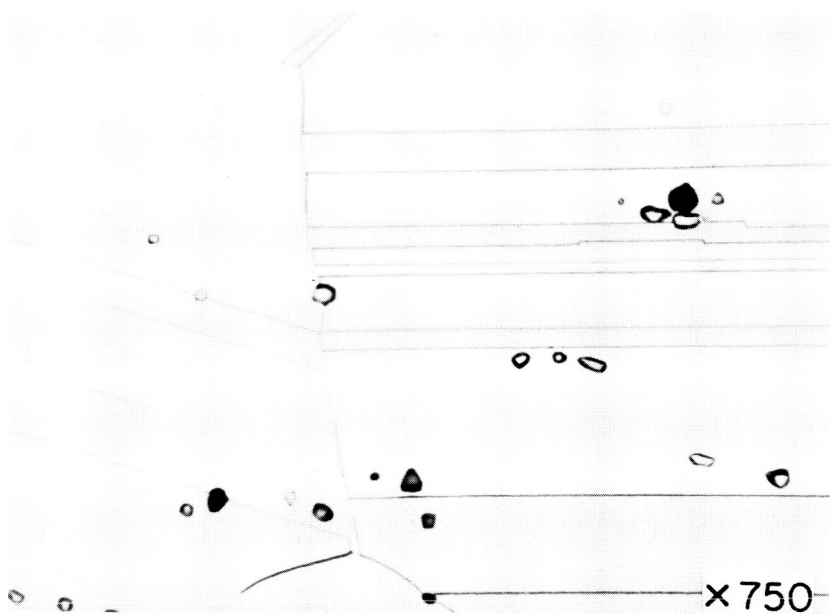Figure 10. - As-cast microstructure of alloy Co-25W-1Ti-1Zr-0.4C.

×250

×750

C-64228

├─────────────┤
i INCH

(a) As rolled.

Figure 11. - Microstructure of alloy Co-25W-1Ti-0.4C
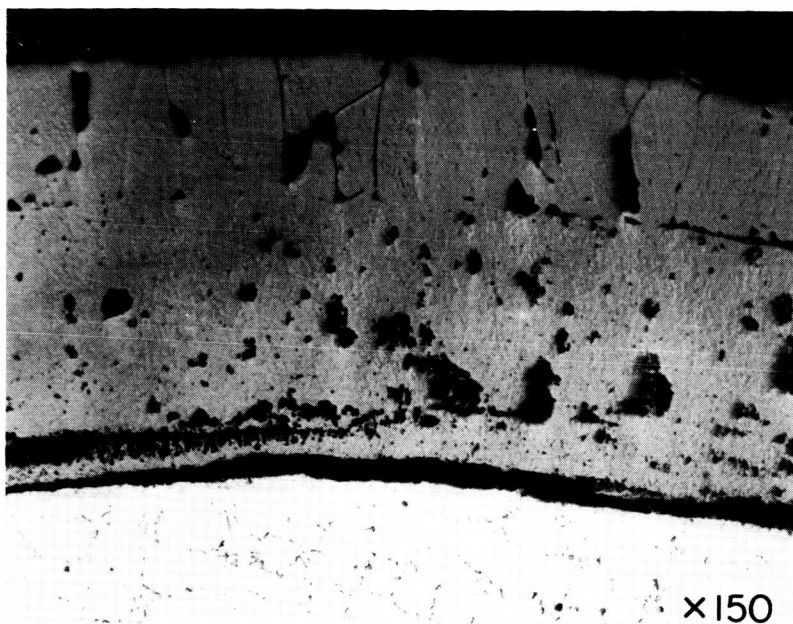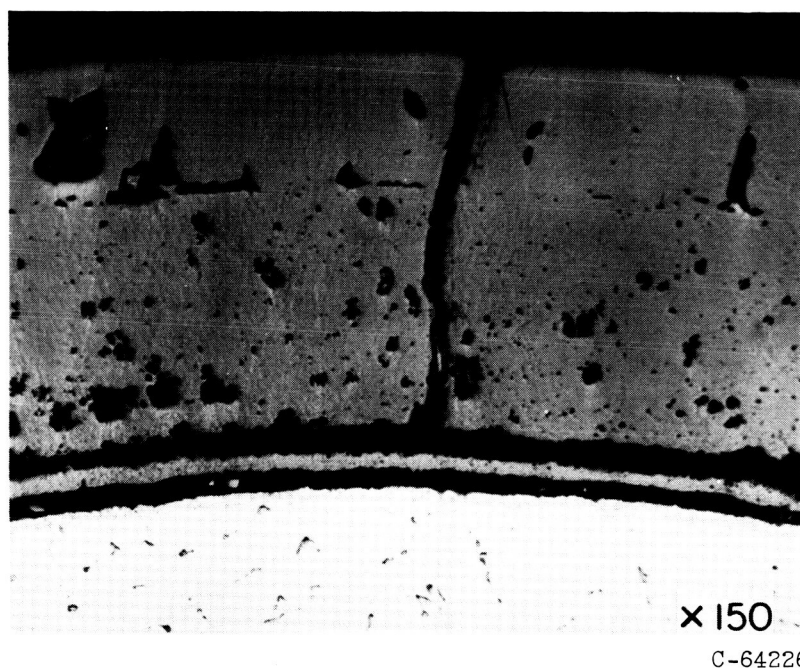sheet, longitudinal section.

× 250

× 750
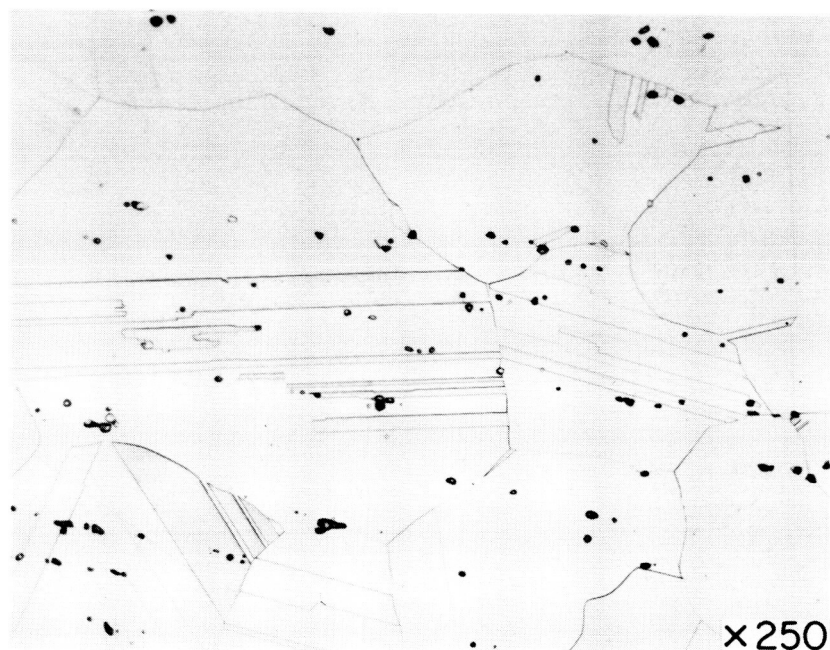
C-64227

| INCH

(b) Solution treated at 2400° F.

Figure 11. - Concluded. Microstructure of alloy Co-25W-1Ti-0.4C sheet, longitudinal section.

(a) Co-25W-1Ti-0.4C.

C-64226

⊢————————⊣
I INCH

(b) Co-25W-1Ti-1Zr-0.4C.

Figure 12. - Microstructure of oxidation test specimens in vicinity of exposed surface after 50 hours of exposure at 1900° F.